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Craniofacial stereo mapping: Improving accuracy with natural points

ABSTRACT

Stereo-photogrammetry has been reported in both photogrammetry and medical journals as the most suitable technique for craniofacial landmark mapping. Various size and shape of control frames were designed to provide three-dimensional object-space control for stereo images. A research was carried out to determine whether the accuracy could be further improved using natural points. In the research, control points and natural points were measured using photogrammetric digitising software and their coordinates computed using bundle adjustment technique. In addition, the six-camera stereo-photogrammetric system was electronically synchronized for optimum accuracy. Subsequently, a digital photogrammetric workstation was used for stereo orientation and stereo-digitising of the anthropometric landmarks. For the accuracy assessment of the 'natural point' technique, absolute orientation was performed on the stereo-model using control-frame control and natural points respectively. The results show that the developed technique achieves an accuracy of 0.6mm at one standard deviation. The best accuracy of the stereophotogrammetric system was 0.25mm.

INTRODUCTION

Craniofacial anthropometric measurements required high quality measuring tools in order to obtain the highest possible measurement accuracy (Farkas et al. 1996). Among the methods used, Stereophotogrammetry was chosen as the best as a non-contact, non-invasive, reproducible, fast, high-accuracy, practical and cost-effective technique measurement of facial morphology (Naftel et al. 2004; Burke et al. 1983; Hay et al. 1985; Majid et al. 2005; Meintjes et al. 2002; Ras et al. 1995; Wagner et al. 2005; Johnston et al. 2003).

Generally, object-space control is required for the stereo orientation of the craniofacial stereo-photographs. The control allows scaling and orientation of the spatial three-dimensional model during absolute orientation. The control frame may be placed over the patient's head (Savara and

George 1984); near both side of the head (Peterson 1993) and (Schewe and Ifert 2000) the control targets were placed on a helmet. These three designs almost certainly covered in all published photogrammetric control configurations (Majid et al. 2005). However, tests show that the recommended location of the control targets on the frame was not suitable for high accuracy stereo-orientation. The accuracy in the Z (along the optical axis) does not satisfy the project requirement of 0.7 mm where the Z position of the landmark is far from the average Z position of the control points (Ghosh 1972: p41). For example, the Z value of the nose is outside the Z zone controlled by the control-board control (Figure 1). The research is to solve the problem by testing the suitability of using natural points, which may be birth mark, acne or scar, as control for stereo-orientation.

Consequently, a method was developed to

obtain accurate coordinates of the natural points. It involves a bundle adjustment of six stereo-photographs taken for the three stereo-models using the control frame. The bundle adjustment computes the coordinate of the natural points. Subsequently, the natural points are used to carry out exterior orientation of the stereo-models.

The objective of the paper is to present the developed technique. The discussion includes: 1) computing the coordinate of the natural points; 2) model orientation using the natural points and 3) analysing the accuracy of the technique by comparing the Z coordinate obtained by the natural points with those obtained by using the control frame.

METHODOLOGY

Stereo-photography

The design of the photography is based on three stereo-pairs of photograph. Six Sony DSC F828 digital cameras were set up 600 mm from the object (mannequin and human face) to capture the stereo images. The cameras were electronically synchronized using a lanc shepherd controller (Graphic Media Research, Minnesota, USA). Figure 1 shows the setup of the stereo-photographic system at School of Surveying, University of Otago.

Calibrating the stereo camera

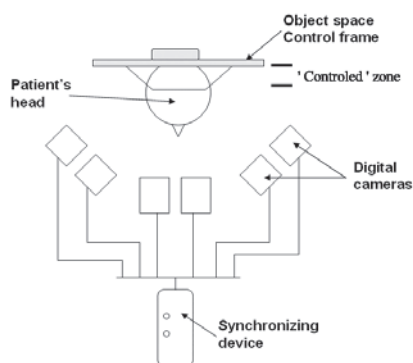


Figure 1: Stereo-photographic system used in the study. Note the distance (Z) from the nose to the control frame and the control zone.

Each camera was calibrated independently using a three dimensional calibration device (Figure 2). The device consists of a camera mount and a 3D test field. Retro-targets were placed in row and column as shown in the figure. The calibration procedure is discussed in Chong and Scarfe (2000) and Majid et al. (2005).

Calibrating the photogrammetric control frame

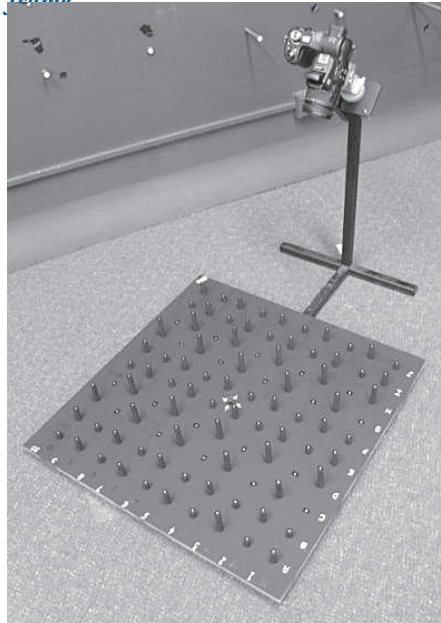


Figure 2: A three dimensional camera calibration test field.

A control frame was built to provide an accurate control for the research (Figure 3). Retro-targets were used to highlight the control points. The control frame also

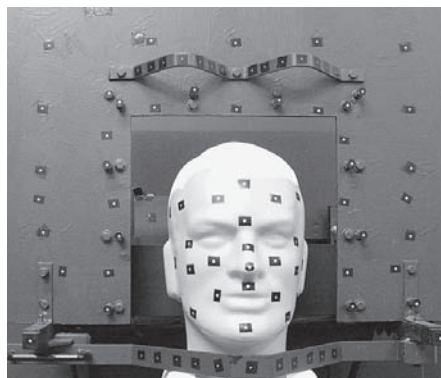


Figure 3: A high-quality control frame with control points and the simulated natural points on the face (both marked with retro targets). Note that the simulated natural points were also used as a test point for distance and angle measurements.

requires accurate calibration. The x, y and z coordinates of the targets were determined using convergent photographs and a bundle adjustment (Chong and Strafford 2002). The coordinates would be used for the exterior orientation of the stereo models and for computing natural points' coordinates.

Data collection

The photography consists of two stages: (1) a set of convergent photographs of the mannequin to determine coordinates of the simulated natural points (see Figure 4) and (2) a set of six stereo-photographs of the mannequin for stereo-digitising of the anthropometric marks and 3D surface (see Figure 5 and Figure 6). In stage (1), six convergent photographs were captured. A scale bar which consists of an invar bar with a target at each ends, was placed in the object space. Stage (2) involved the capturing of 60% stereo-photogrammetric overlap of the mannequin from three different stereo camera positions which covered the craniofacial area. The camera

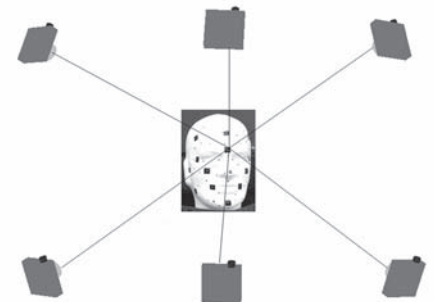


Figure 4: Convergent photographs for the bundle adjustment of the test point coordinates. Note that the photographs were not used for stereo-digitising on photogrammetric workstation.

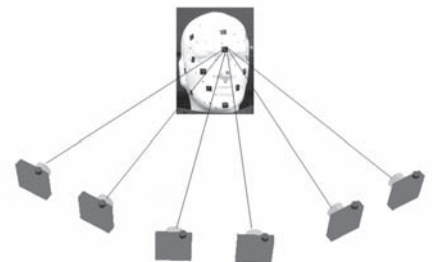


Figure 5: Normal stereo-photographs for stereo-digitising of the anthropometric marks. Note the camera configuration and the bundle of rays to the natural point and test points.

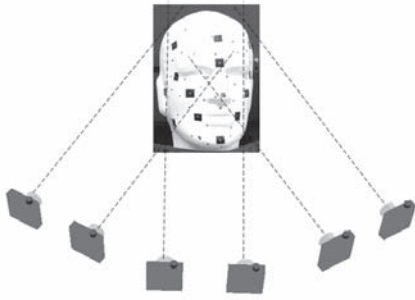


Figure 6: The stereo photographs of the test object showing the overlap areas. The configuration is also shown in Fig. 1.

lens to object distance (object distance) was set to 600 mm.

Data processing

There are four stages for this part of the research. The stages are discussed below.

i) Stage 1: *Obtaining object-space coordinates of control frame points.*

Australis photogrammetric software was used to mono-digitise image coordinate (x and y) of the retro-targets on the control frame and test points on the six convergent photographs. Retro-target on the scale bar were also digitized. A bundle adjustment was performed on the image coordinates of the digitized points using Australis. The scale bar was used in the adjustment to scale the object-space coordinates. The output of the adjustment is a set of accurate coordinates for the control and test points.

ii) Stage 2: *Obtaining object-space coordinates of the natural points.*

Also mono-digitising was performed on all six stereo-photographs. However, natural points were added to the list of points for digitising. The scale bar targets were not observed because the object-space would be scaled by control-frame coordinates which were obtained in Stage 1. A bundle adjustment was performed on the image coordinates of the observed points. It must be noted that a triangulation must be carried out if there are very few observed points. This is because the bundle adjustment requires an appropriate number of degrees of freedom to achieve a high quality Least Squares solution.

iii) Stage 3: *Obtaining object-space coordinates of test points using stereo-digitising technique.*

The Stereo Orientation module, DVP software (DVP, Canada) was used to establish stereo-orientations (interior, relative and absolute) for stereo-digitising and the vectorisation module was used to obtain the 3D coordinates of the test points (Figure 7). In this study, the stereo-models (front view, left view and right view) were processed separately. Absolute orientation of each model involved two separate sets of three-dimensional ground controls, namely: (a) signalled targets on the control frame; and (b) signalled targets on the face or natural points. After each absolute orientation, the 3D coordinates of the test points was measured three times stereoscopically and the average of the coordinates was calculated

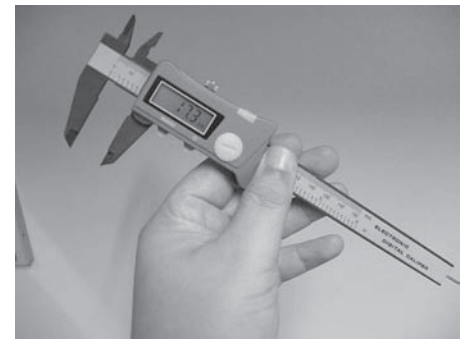


Figure 8: A digital calliper used for direct measurement on the mannequin.

for comparison.

iv) Stage 4: *Obtaining 3D distances between test points using calliper technique.*

The digital calliper with the accuracy of 0.1mm was used to measure the distances between the selected test points on the craniofacial surface directly. The calliper was calibrated to ensure accurate measurement. Each distance was measured three times and the average of the distances calculated. Figure 8 shows the digital calliper used in the measurements.

RESULTS AND ANALYSIS

The accuracies of measurements of the control frame and the natural point methods were first determined by using standard errors of control coordinates in the absolute orientation. The standard error depends on the accuracy of three-dimensional ground control coordinates and the location of the control on the model. Table 1 shows the standard errors obtained from the methods. The control was well distributed on the stereomodel. The results show a significant improvement in the size of the error.

Further analysis involved studying the vector, distance and angle measurements between sets of test points. In the study, the distances and angles obtained by an independent method (bundle adjustment method) was used as a *gold standard* to verify the accuracy of the techniques. Also, the analysis involved the comparison of the Z values of the stereo-photogrammetric measurements obtained by the techniques.

(a) *Analysis of the 3D distance and angle*

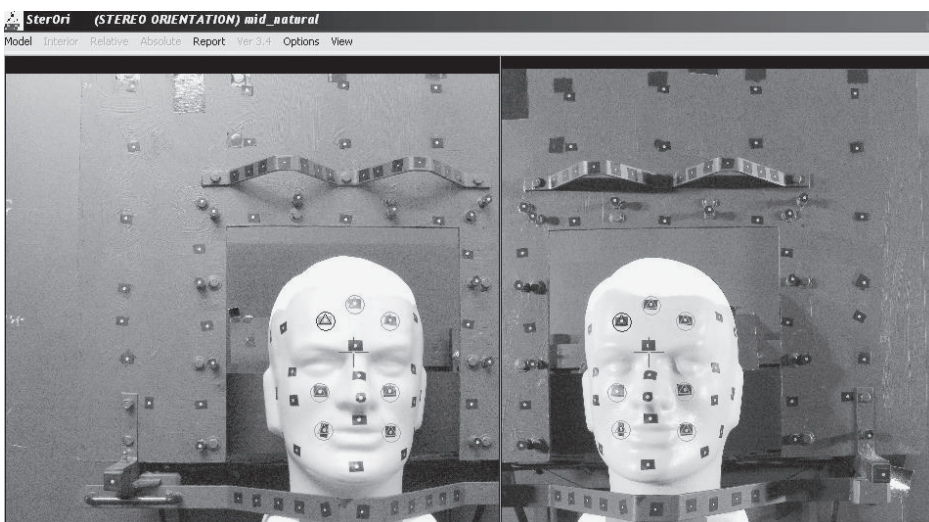


Figure 7: Stereo digitising of test points using DVP software.

Table 1. Optimum standard error of stereo-photogrammetric absolute orientation.

Methods	Standard errors in x, y and z axis. (mm)
Control frame method	Front model (0.347, 0.303, 0.533)
	Left model (0.364, 0.225, 0.266)
	Right model (0.304, 0.222, 0.237)
Natural point method	Front model (0.063, 0.117, 0.246)
	Left model (0.125, 0.112, 0.310)
	Right model (0.216, 0.112, 0.320)

The analysis involved sixteen anthropometric points which were marked by signalised targets (Fig. 9). There were four types of measurement obtained from four techniques. The techniques were: 1) independent bundle adjustment; 2) control frame method; 3) natural point method; and 4) caliper method. Independent bundle was used as the gold standard. The comparison was carried out using

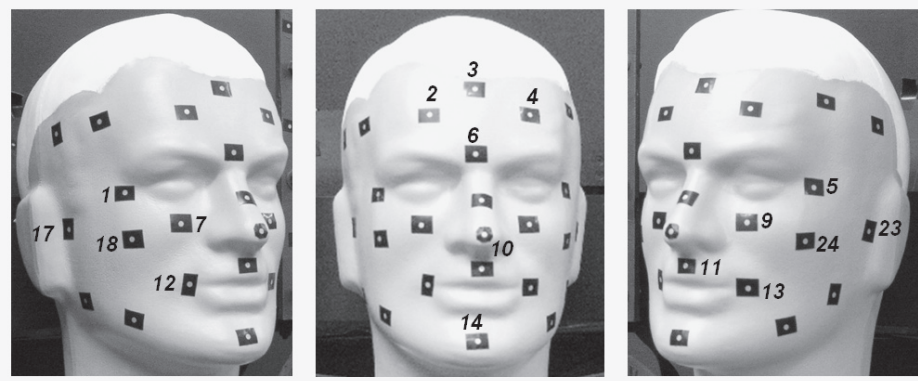
the mean, variance and standard deviation of the measurement difference. Tables II and III show the results of the analysis.

(b) Analysis of depth value

The study of the depth value in the research was to prove that the use of natural points as object-space control for craniofacial stereo-photogrammetric mapping improves

the accuracy of anthropometric landmark measurements. The depth value is defined as the height difference between the average datum (the average height of all object-space controls of a model) to a measured points (e.g. anthropometric landmarks). The depth percentage (%) is the ratio of the depth value and the object distance in percents. As discussed elsewhere, in aerial stereo-photogrammetric mapping, the terrain height variation should not be more than 10% of the flying height in order to obtain accurate height measurements (Ghosh 1972: p41). The requirement should be applied to close-range stereo-photogrammetry. That is, the computed height of a measured points in a stereomodel would have an accurate height if the depth value of the point is within $\pm 10\%$ of the object distance. For example, for the object distance of 600mm, the optimum depth value is ± 60 mm. In the analysis, the depth percentage and the depth value of measured test landmarks for both techniques were examined (Figure 10).

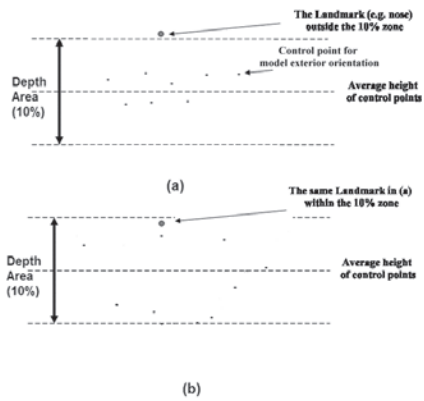
The statistical analysis involved two variable regressions between the errors in z coordinates versus the depth percentage for each test point in both methods. The plots of the results are provided in Figure 12 and Figure 13. Both plots show consistent results in which an increase of depth percentage there is an increase in the error of z coordinate. The results also show that the natural point method is more accurate than the control

**Fig. 9. Position of anthropometric points on the mannequin.****Table 2: Distance measurement differences.**

From point	To point	Calliper vs. bundle method (mm)	Natural point method vs. bundle method (mm)	Control frame method vs. bundle method (mm)
2	4	0.18	0.08	1.72
3	6	0.35	0.44	0.36
6	10	0.21	1.44	0.5
12	13	0.11	0.50	4.85
1	5	0.11	0.61	7.66
17	7	0.20	0.37	10.20
9	23	0.15	2.00	12.22
4	24	0.11	0.12	0.90
2	18	0.17	0.34	2.16
3	14	0.32	0.22	3.86
Statistics	Mean	0.19	0.61	4.43
	Variance	0.01	0.38	18.07
	Std Dev	0.08	0.62	4.25

Table 3: Angle measurement differences. Note that the calliper measurement excluded the angles not measured physically.

Three points involved (first – middle – last)	Natural point method vs. bundle method (deg)	Control frame method vs. bundle method (deg)
5-23-13	2.04	1.81
1-17-12	2.08	2.44
3-17-14	2.08	6.61
3-23-14	1.13	6.15
<i>Mean</i>	1.83	4.25
<i>Variance</i>	0.16	4.60
<i>Std Dev</i>	0.40	2.14

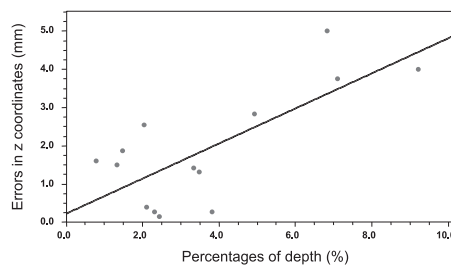
**Fig. 10. Location of test landmarks and the average height datum of (a) control point method and (b) natural point method.**

frame method.

An F statistic test was conducted to verify the accuracy of the natural point method. The test involved the analysis of population variance to test the significance of difference between the two methods. The null hypothesis (the accuracy of the two methods are the same) was tested. The null hypothesis was rejected and it proved that the accuracy of the two methods is not the same. In other words, natural point method is more accurate.

CASE STUDY

To verify that the developed method was really accurate to support the craniofacial anthropometric mapping, a facial surface with signalized target (representing natural points and test points) was used in the case study (see Figure 14). The face, control frame and photography using the six synchronized digital cameras were a duplicate of the previous test study (Figure 1). Photogrammetric

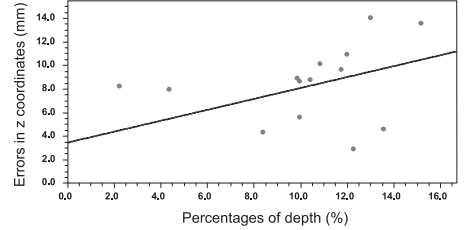
Figure 11: Depth percentage analysis – natural point method.**Figure 11: Depth percentage analysis – natural point method.**

triangulation method was used to calculate the three dimensional coordinates of the signalized target accurately using Australis software. Both control frame and natural point method were carried out separately in the exterior orientation of the three pairs of stereo models. Nine 3D measurements between targets were performed stereoscopically. The direct measurements were also performed using calliper as a comparison with the proposed method. All the measurements were repeated three times in order to make sure that each technique was reproducible.

Table 5 shows the results of study. The natural point method was found to be more accurate with standard deviation of 0.65 mm compared to 1.94 mm from the control frame method.

DISCUSSION

The use of natural point's method as a object-space control was found to be an effective method to improve the accuracy of the craniofacial stereo mapping. By using the natural points method, there is no need to shorten the camera-object distance. Consequently, the optimum coverage of

Figure 12: Depth percentage analysis – control frame method.**Figure 12: Depth percentage analysis – control frame method.**

three models for the craniofacial area was maintained as designed. Good quality natural points were easily found and they were well-distributed in the overlapping areas.

Only an additional one hour was needed to run the triangulation process to obtain the 3D coordinates of the selected natural points. Australis camera calibration software was used to digitize the natural points and to run the triangulation adjustment. Since the same software was used for calibrating the stereo cameras, digitising the points and computing the coordinates of the natural points, there is no additional cost involved.

CONCLUDING REMARKS

Research is in progress to use the natural points method for the living craniofacial patients. In addition, tests are being carried out on the use of near infrared filter for the high accuracy of natural points identification and measurements. The results of the research will be published in near future.

ACKNOWLEDGEMENT

The authors acknowledge the support of

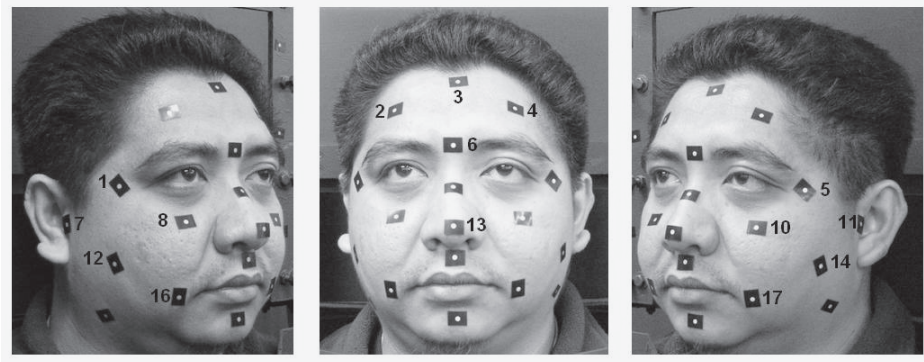


Figure 14: Human face with signalled targets to represent the natural points and test points.

the Ministry of Science, Technology and the Environment (MOSTE) Malaysia for this multi-million dollar craniofacial reconstruction database project (2002 Intensified Research Prioritised Area (IRPA), Eighth Malaysian Plan research grant), and the School of Surveying, University of Otago.

REFERENCES

- Burke, P.H., Banks, P., Beard, L.F.H., Judith, E and Huges, C., (1983). Stereophotographic measurement of change in facial soft tissue morphology following surgery. *British Journal of Oral Surgery*. 21: 237-245.
- Chong, A.K. and Scarfe, B., (2000). Camcorder Calibration. *New Zealand Surveyor*, 290: 17-21. 10.
- Chong, A.K., and P. Strafford, (2002). Underwater digital stereo-observation technique for Red Coral study. *PE&RS. USA*. 68(7): 745-751.
- Farkas, L.G. (1996). Accuracy of Anthropometric Measurements: Past, Present, and Future. *Cleft-Palate Craniofacial Journal*, Vol 33, No. 1.
- Ghosh, S.K., 1972. *Theory of Stereophotogrammetry*. Edwards Brothers, Inc. Ann Arbor, Michigan. 206 pages.
- Hay, K.D., Rivert, L.J., Bennet, K.R and Reade, P.C., (1985). Photogrammetry used to assess post-operative facial swelling in a drug trial. *British Journal of Oral and Maxillofacial Surgery*. 23: 103-111.
- Johnston, D.J., Millet, D.T, Ayoub, A.F and Bock, M., (2003). Are facial expressions reproducible? *Cleft-Palate Craniofacial Journal*, 40(3): 291-296.
- Majid, Z, A. K.Chong, Ahmad, A, Setan, H, Samsudin, A.R, (2005). Photogrammetry and 3D Laser Scanning as Spatial Data Capture Techniques for a National Craniofacial Database. *The Photogrammetric Record* 20(105): 1-19 (March 2005).
- Meintjes, E.M, Douglas, T.S, Martinez, F, Vaughan, C.L, Adams, L.P, Stekhoven, A and Viljoen, D., (2002). A stereo-photogrammetric method to measure the facial dysmorphology of children in the diagnosis of fetal alcohol syndrome. *Medical Engineering & Physics* 65: 683-689.
- Mitchell, H.L. and Leemann, T., (1996). Issues in medical photogrammetry in the digital imaging era. *International Archives of Photogrammetry and Remote Sensing*, 31(B5): 362-367.
- Naftel, A.J, and Trenouth, M.J., (2004). Stereo-assisted landmark detection for the analysis in 3-D facial shape. *Medical Informatics* 29 (2): 137-155.
- Peterson, A.E., Durdle, N.G., Raso, V.J. and Hill, D.L., (1993). Calibration of video cameras for scoliosis mapping. *Geomatica*, 47(1): 29-38.
- Ras, F, Ginkel, F.C and Anderson, B.P., (1995). Method for quantifying facial symmetry in three dimensions using stereophotogrammetry. *Angle Orthodontist* 65(3): 233-239.
- Savara, B. and George F.G., (1984). Biostereometrics for patients with craniofacial malformations. *Proceedings. American Society of Photogrammetry, Fall Convention, Fort Worth, Texas*. 941pages: 833-842.
- Schewe, H. and Ifert, F., (2000). Soft tissue analysis and cast measurement in orthodontics using digital photogrammetry. *International Archives of Photogrammetry and Remote Sensing*, 33(B5): 699-706.
- Wagner, H, Wiegmann, A, Kowarschik, R and Zollner, F., (2005). *3D measurement of human face by stereophotogrammetry*. *DGaO Proceedings*. ISSN: 1614-8436.

Table 4. Results of the case study. Note that the distance calculated from the triangulation method was selected as a 'gold

From point	To point	Caliper vs. triangulation (mm)	Natural point method vs. triangulation (mm)	Control frame method vs. triangulation (mm)
2	4	0.11	1.36	3.57
3	6	0.03	0.77	1.61
6	13	0.56	2.01	1.87
16	17	1.60	0.20	0.81
1	5	0.30	0.70	7.64
7	8	0.66	2.00	1.67
10	11	0.63	0.66	2.87
4	14	1.09	1.10	3.56
2	12	0.31	0.15	1.44
Statistics	Mean	0.59	0.99	2.78
	Variance	0.22	0.42	3.77
	Std Dev	0.50	0.65	1.94